Calibrated Basin Modelling to Understand Hydrocarbon Distribution in Barmer Basin, India*

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Abstract

The Barmer Basin is a Tertiary intra-cratonic rift basin located in the western part of India with around 6,000 m of sediment fill overlying Proterozoic basement. The main period of exploration began in 2000, with seismic being acquired over most of the basin and some 160 exploration and appraisal wells having been drilled to date. In addition, a vast amount of data has been collected on source rocks, oils, heat flow measurements and rock properties in both wells and outcrop sections. This data has been incorporated into a detailed petroleum system analysis.

An integrated approach was adopted for construction of a robust regional basin model, which incorporates a set of gross depositional environment maps (GDE) for source (Barmer Hill and Dharvi Dungar), reservoirs (Fatehgarh, Dharvi Dungar and Thumbli) and seals (both intraformational and regional). Uplift/erosion estimates calibrated to apatite fission track and vitrinite reflectance data as well as paleobathymetry were used for burial history reconstruction. A calibrated heat flow model has been applied for building the 1D-maturity models across the basin. Paleo-heat flow maps were calibrated to vitrinite and Horner corrected borehole temperature data. A regional pseudo-3D basin model with appropriate thermal scalars was constructed using calibrated 1D models across the basin. For the Barmer Hill Formation, source rock specific kerogen kinetics data were used to define the source rock model. Original total organic carbon (TOC) and original hydrogen index (HI) were back computed from laboratory derived Rock-Eval data. The original TOC and HI mapping was governed by source rock GDE maps. The resulting regional pseudo-3D migration model was calibrated to the known discoveries and shows throughout the basin.

Results of the integrated basin modelling confirm the presence of multiple source units in the basin. The Barmer Hill Formation source rock is the main contributor of generated hydrocarbons. Source rock data analysis shows that northern Barmer Basin is enriched with oil prone lacustrine source facies whilst the southern Barmer Basin contains both oil and gas prone facies. The migration model indicates that local sub-grabens are able to charge the adjacent traps and that long distance migration is not required. The 3D basin model has provided critical insights to the spatio-temporal distribution of migrated hydrocarbons and helps predict type and physico-chemical properties of the fluids.

Introduction

The Barmer Basin is a late Cretaceous to early Tertiary intra-cratonic rift basin located in the western part of Rajasthan, northwestern India. Sediment thickness exceeds 6 kilometers in the main rift depocenters and overlies Proterozoic basement (Figure 1). The basin is a typical asymmetric rift and connects to the better-known Cambay Basin to the south. The most significant reservoir in the basin is the late Cretaceous to early Palaeocene syn-rift Fatehgarh Formation, although basement and younger reservoirs are also present. The main source rocks across the basin are lacustrine shales and diatomites of the Barmer Hill Formation, although other stratigraphic units contribute subordinate amounts of hydrocarbon to the petroleum system. The Dharvi Dungar Formation represents the latest syn-rift unit and records the continental filling of the rift accommodation space, and is succeeded by the post-rift Thumbli Formation alluvial plain clastics. A major depositional hiatus in the Oligocene and tilted uplift in the Miocene completes the basin history (Figure 1).

Cairn has been exploring the basin since 1999 and has acquired seismic over most of the basin, and some 150 exploration wells have been drilled with a success rate of approaching 50%. Extensive data on source rock properties, heat flow, and reservoir and seal rock properties have been collected from wells and outcrops. This data has been incorporated into a pseudo-3D petroleum systems model of the basin, which is used to predict and risk the probable distribution of undiscovered oil and gas as well as ask ‘what if?’ questions to develop an understanding of the petroleum system to geological uncertainties in the basin.

Data, Methods and Workflows used in the Modelling

The extensive input and calibration data set used for basin modeling comprises seismic, petrophysical well data, core, geochemistry (fluids and rock), fission track analysis fluid inclusion stratigraphic data and temperature data from wells. The basin model incorporates gross depositional environment (GDE) maps as polygon surfaces across the whole basin (Figure 2) for the source rock horizons (Barmer Hill, Dharvi Dungar), and the main reservoir horizons (Fatehgarh, Dharvi Dungar and Thumbli) and seals.

Wherever possible these were conditioned with seismic attribute maps. Rock types, facies distributions and rock properties were assigned to each of the surfaces in the model. The examples shown in Figure 2 represent one of several reservoir units and the main source rock unit, the Barmer Hill Lake. These maps enable significant definition of both source and reservoir distribution to be incorporated into the model which better constrain the oil and gas generation potential as well as migration and trapping components of the basin. Fault planes were incorporated into the surfaces and are included in the migration models.

1D burial models (Figure 3) were based on well stratigraphy including erosional events, with erosion being calibrated to vitrinite reflectance, spore color index and apatite fission track data and modeling, with regional maps of erosion being created across the basin for burial history reconstruction. The heat flow model (and its sensitivities) through time was developed from basin structural geometry revealed in regional 2D seismic data and lithologies from well data, with palaeo-heat flow calibrated to vitrinite data and present day heat flow calibrated to Horner-corrected borehole temperature data.

Rock-Eval parameters Hydrogen Index (HI) and Oxygen Index (OI) were used to characterize the source rocks in the basin and construct a pseudo-Van Krevelen diagram to define the source-rock kerogen type and richness. This data clearly reveal that multiple source rocks are present in the basin other than the main Barmer Hill Formation source rock, with a significant potential in the younger Dharvi Dungar Formation (Figure 4).

Kerogen kinetic data determined from key source rock horizons sampled in core was used for building the source rock model (Figure 5). A single activation energy was used in the northern part of the Barmer Basin based on the presence of a distinct lacustrine algal kerogen type whilst for the southern part of the basin a range of activation energies were used because of the mixture kerogen types present in the source rock section.

The original total organic carbon (TOC) and original hydrogen index (HI) were estimated using commercially available algorithms. The distribution of the original TOC and HI across the basin was constrained from hand drawn depositional environment maps calibrated to seismic sequence stratigraphic interpretations and well data (Figure 6). The highest original TOCs and HIs are present in the northern Barmer Basin.

Composite seismic depth maps were used a key input for 3D maturity mapping (see Figure 7). The calibrated 1D models were used for regional pseudo-3D basin model construction. Appropriate thermal scalars were applied for lateral and vertical thermal variations through geological time. The resulting maturity model indicates that the Barmer Hill Formation is typically oil mature in the northern

Barmer Hill but much more gas matured in the southern, deeper part of the Barmer Basin. This prediction is supported by the abundance of biomarker data in the northern part of the basin compared to the southern part of the basin.

The regional 3D migration model was calibrated in a series of validation simulations with known discoveries in the basin and a well "shows" database, which incorporates FIS, gas log, wireline log and core indications of hydrocarbon presence. The timing of hydrocarbon generation and volumes expelled was calculated using the original HI, TOC and the measured kerogen kinetics.

Highlights of the Generation and Migration Modeling Results

The basin modelling simulations undertaken in the Barmer Basin confirm the presence of multiple source rock units in the basin that have contributed to the petroleum system. The Barmer Hill Formation source rock is by far the main contributor to the active petroleum system, and the source-rock data analysis shows that northern part of the Barmer Basin is enriched with oil prone lacustrine source facies and has been a prolific generator of hydrocarbons. Simple mass-balance calculations indicate an order of magnitude more oil has been generated then has so far been discovered. By contrast, the southern part of the basin contains both oil and gas prone facies, but has generated lower volumes of hydrocarbons.

The migration model indicates that the local sub-grabens between the large structural highs in the basin provide direct, short distance charging to the adjacent traps sufficient to charge all the multi-billion barrel discoveries to date. However, significant long distance re-migration took place during Miocene uplifting and basin tilting resulting in complex compositional charge and phase distribution. Vertical leakage of hydrocarbons generated from the Barmer Hill Formation out of early Fatehgarh Formation reservoirs to charge stratigraphically younger reservoirs is shown to be possible, and supported by geochemical data. The calibrated 3D basin model provides critical insight to the spatio-temporal distribution of migrated hydrocarbons, the physico-chemical properties of the hydrocarbon fluids (Figure 8) and indicates prospective areas in the basin that are currently being investigated.

Acknowledgements

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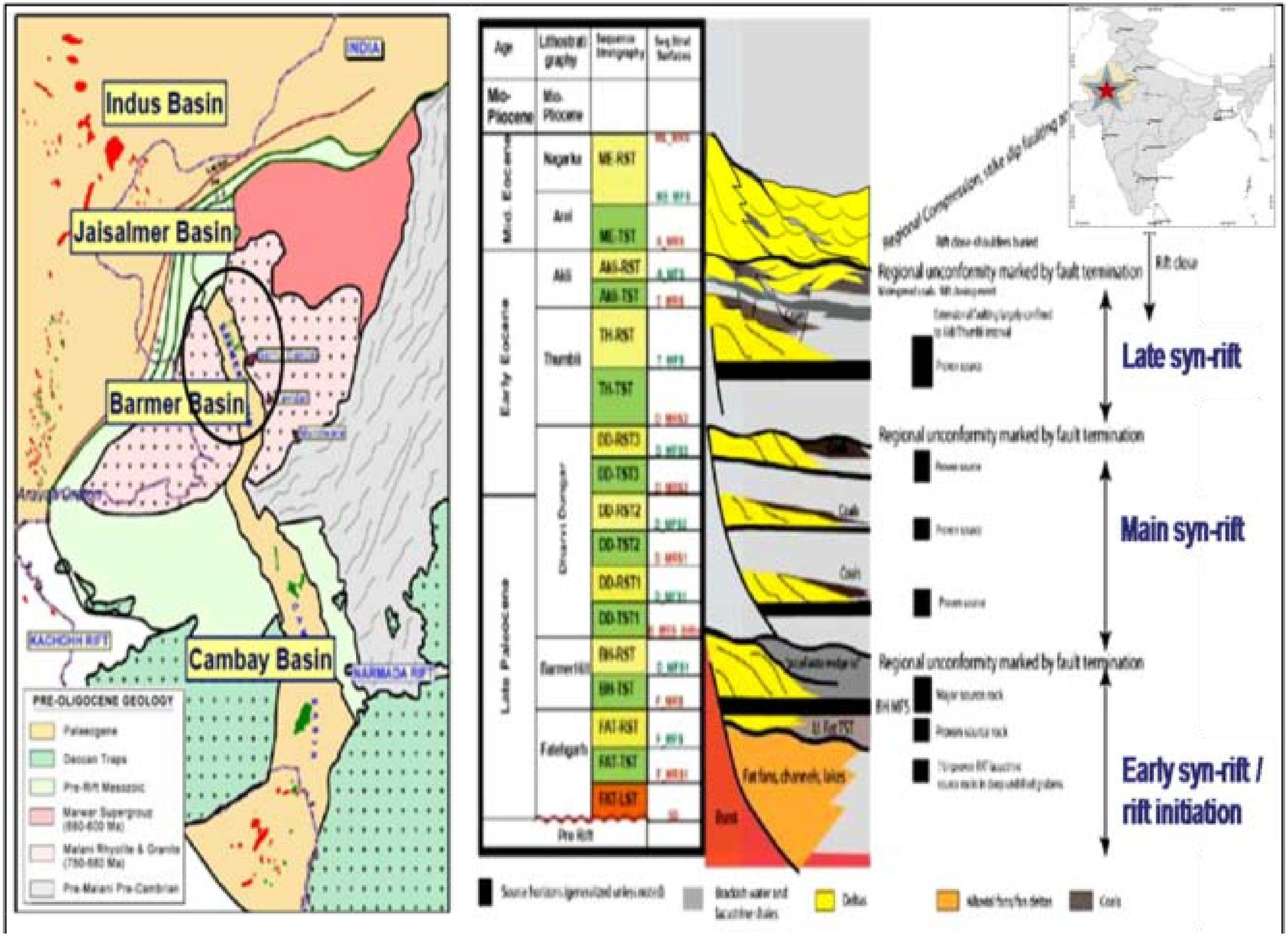

Figure 1. Location of the Barmer Basin and a summary of the main stratigraphic elements of the basin.

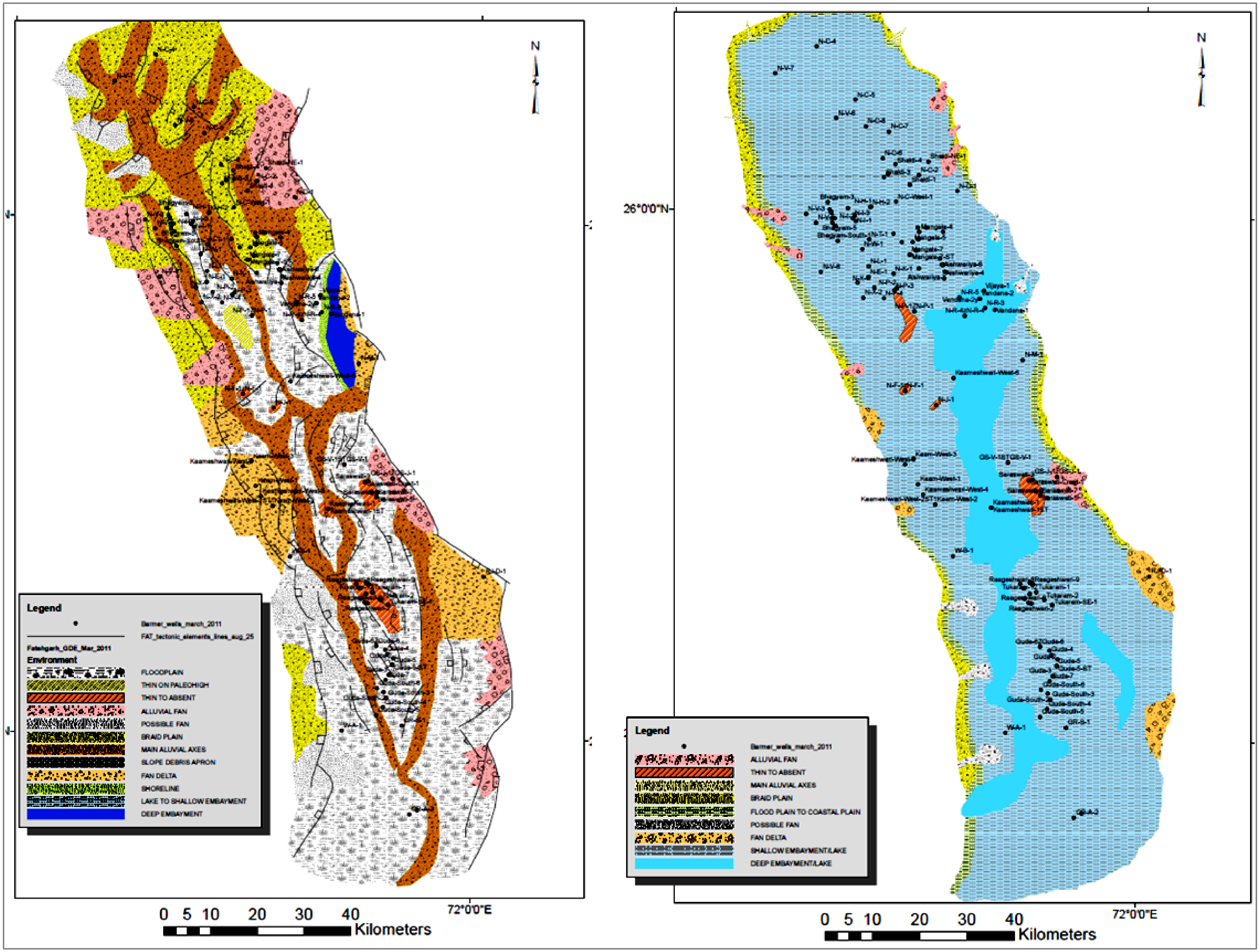

Figure 2. Gross depositional environment (GDE) maps of example reservoir and source facies in the Barmer Basin

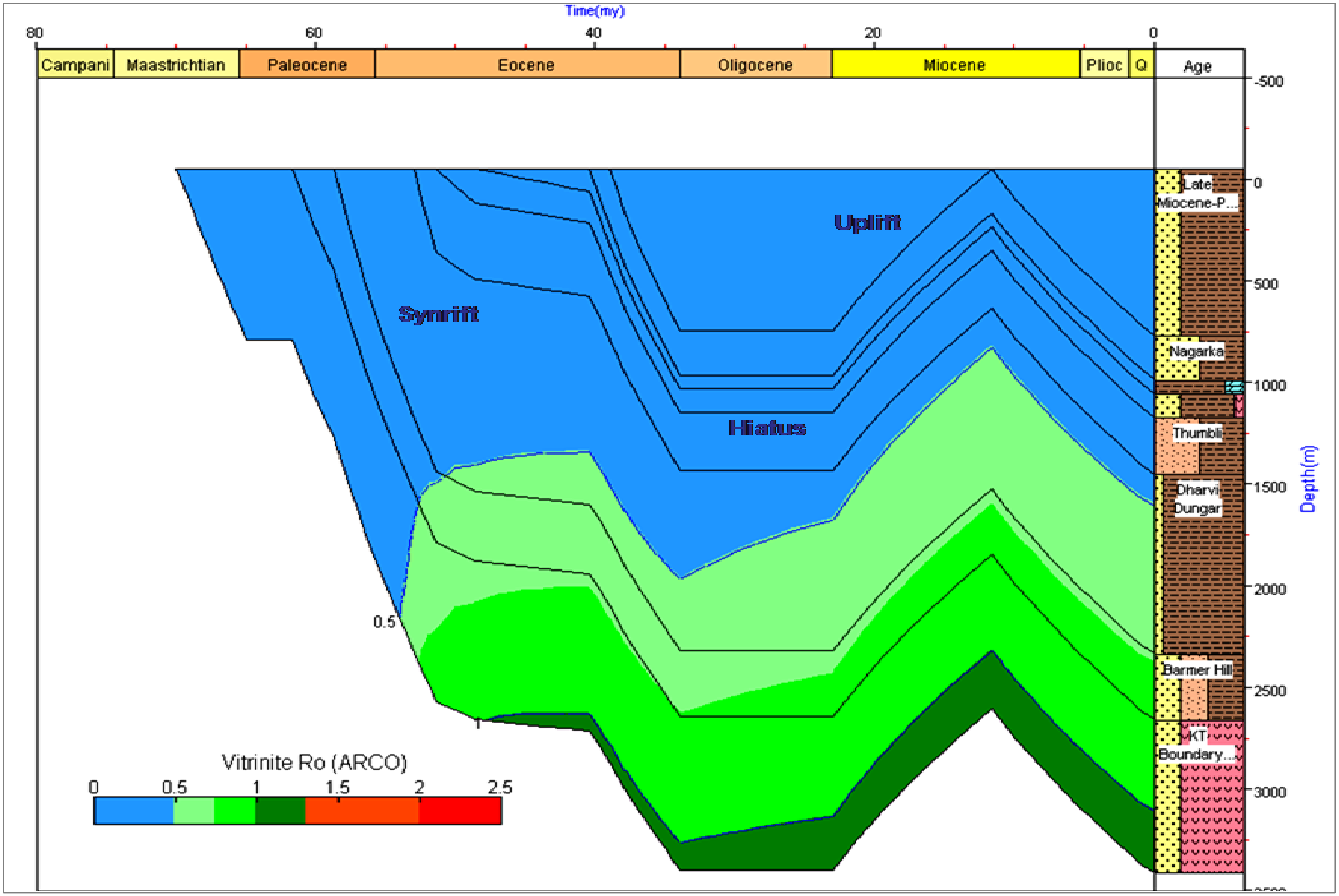

Figure 3. An example 1D burial model with maturity windows superimposed illustrating the late Cretaceous - early Tertiary rifting event and a calibrated uplift event.

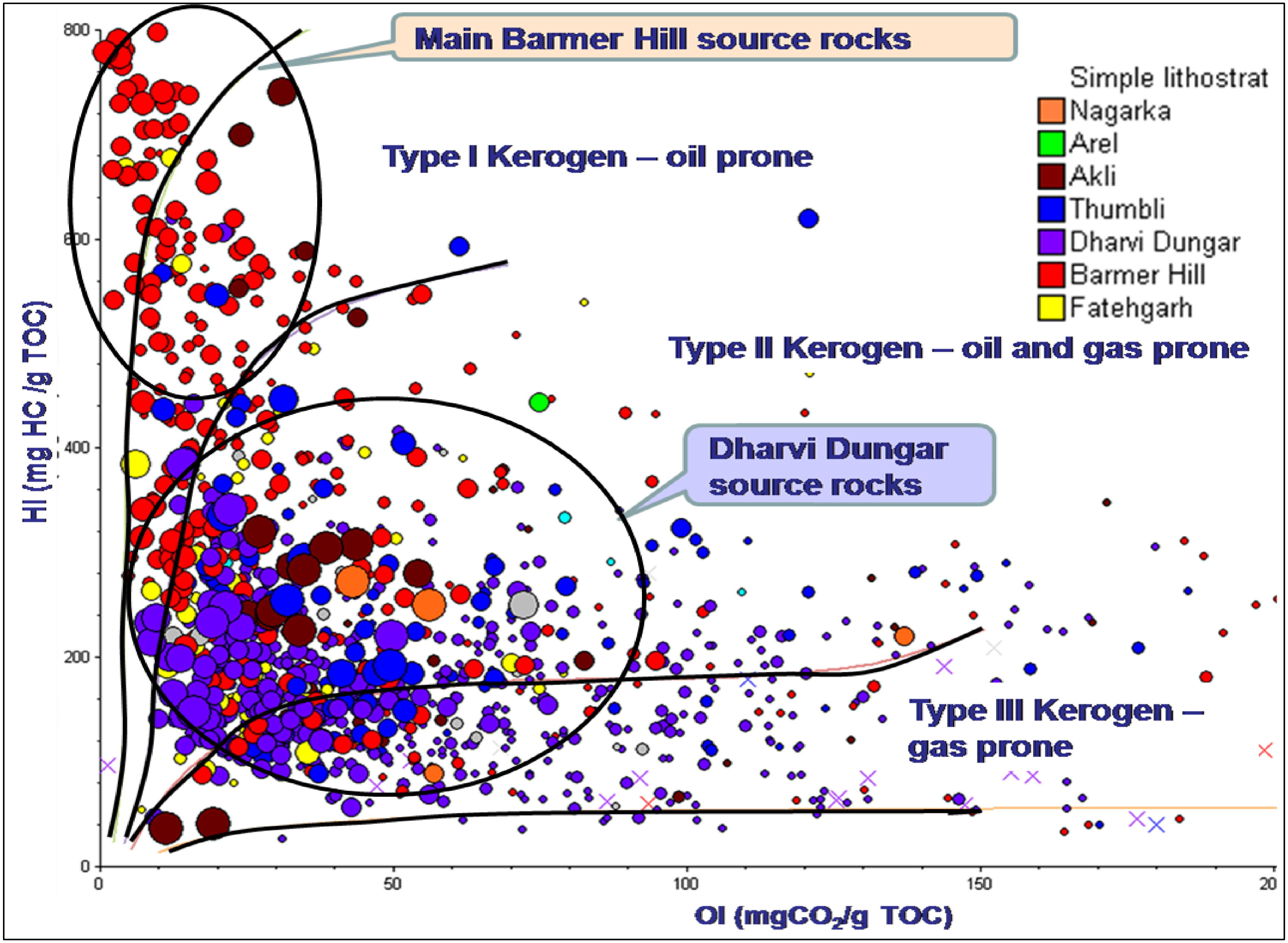

Figure 4. Pseudo-Van Krevelen diagram for representative source rock samples across the Barmer Basin showing the presence of the distinctive type I algal lacustrine source facies of the Barmer Hill Formation, mixed type II source facies in the Dharvi Dungar Formation and presence of type III source facies in other stratigraphic units.

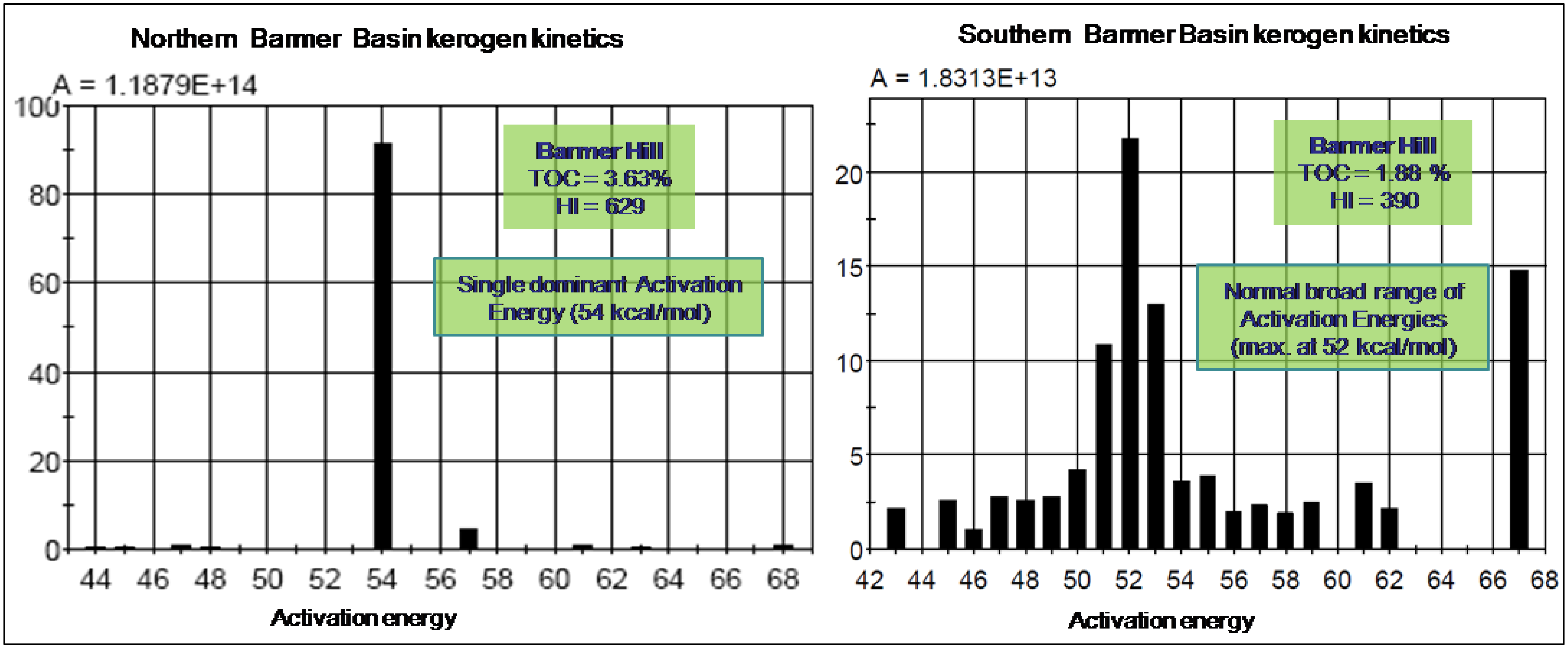

Figure 5. Geographic variation in kerogen kinetics in Barmer Hill Formation.

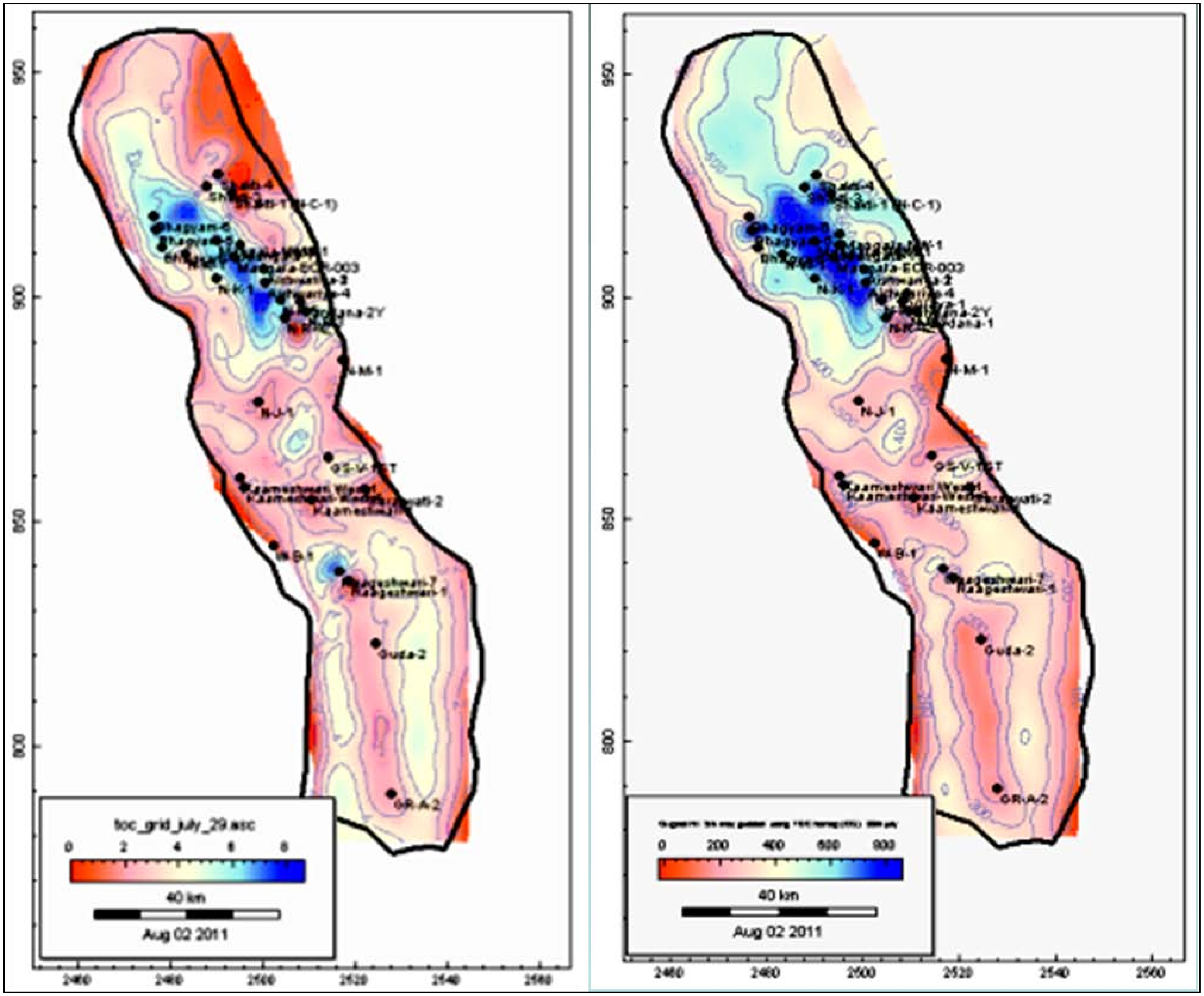

Figure 6. Example indicative calculated maps indicating the original total organic carbon and hydrogen index in the Barmer Hill Formation across the basin.

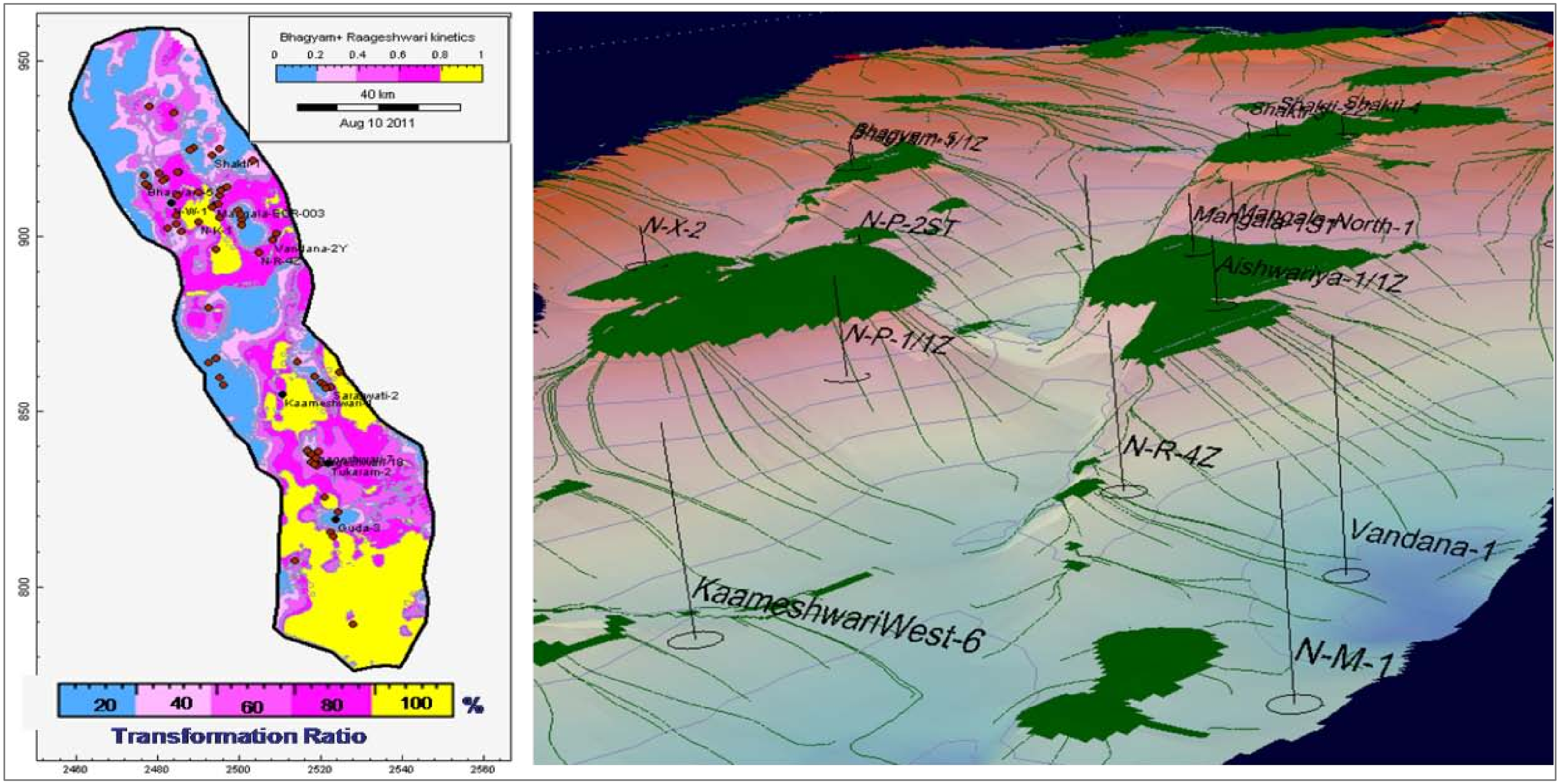

Figure 7. An example maturity map and migration model from a pseudo-3D simulation result for the Barmer Basin. The maturity map is based on Barmer Hill Formation source rock kinetics, and the migration model illustrates one realisation for the northern part of the basin. Green is oil migration path and charge.

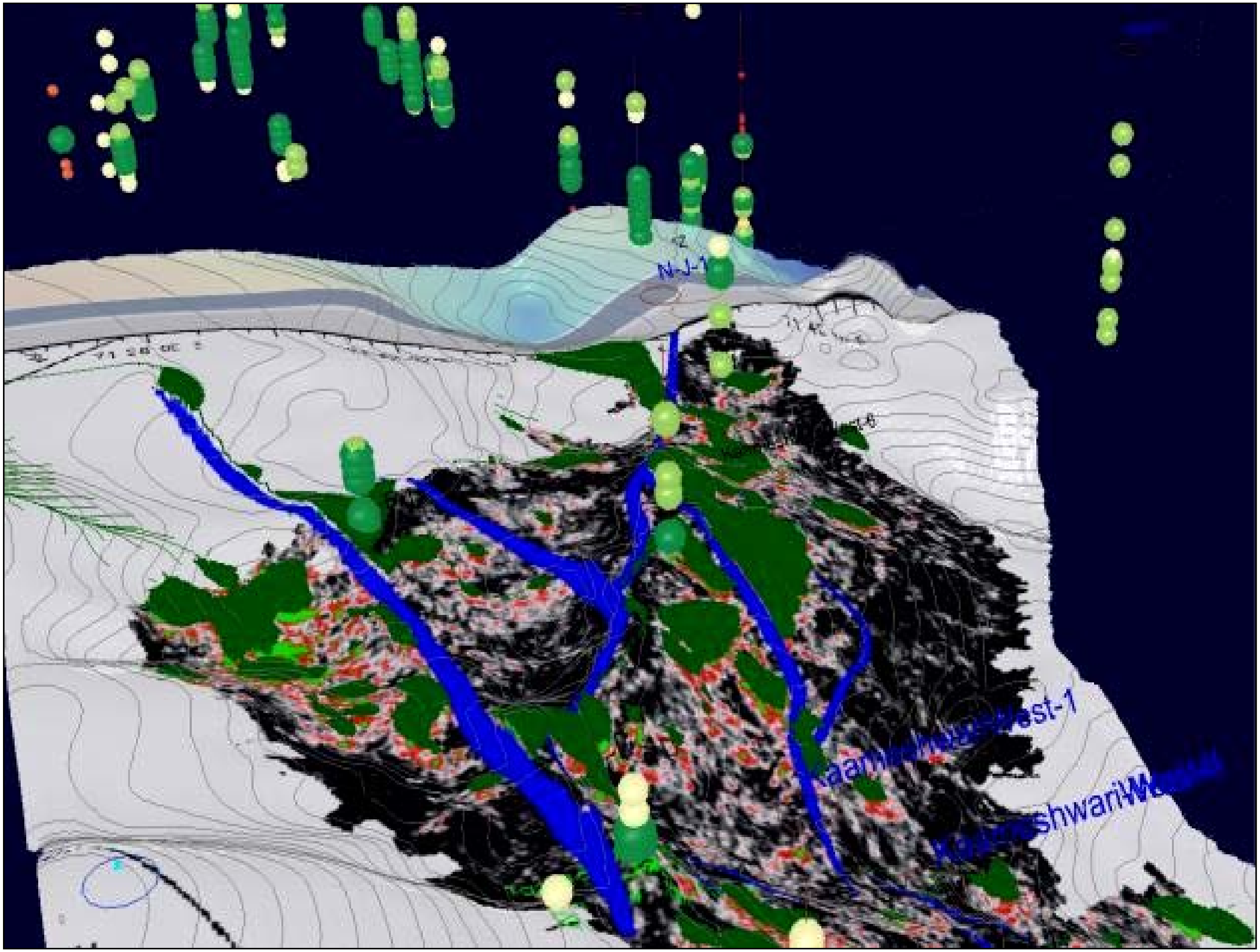

Figure 8. Example of a migration model simulation conditioned with seismic amplitudes to predict oil accumulations at the prospect scale, incorporating faults and fault properties.